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MODELLING THE LONG-TERM COURSE OF NON-FLUSHED RESERVOIR SEDIMENTATION AND ESTIMATING THE LIFE OF DAMS

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ABSTRACT

An analysis of hydrologic and geodetic data from numerous reservoirs lying in different climatic zones, has allowed the two main phases in filling the reservoir during its life to be distinguished, firstly silting of an originally deep reservoir, and secondly silting of a reservoir which has become shallow or initially was not deep. During the first phase, the reservoir plays a role as an accumulator of sediment, so that its trap efficiency for total mineral material is much reduced, and its trap efficiency for suspended load decreases to zero. This phase ends when the mean depth reaches a critical value which is specific for each reservoir. During the second phase, shallowing of the reservoir is much slower, and over short time periods it can play a role as a net exporter of sediment. A general model of reservoir sedimentation is proposed and is tested by data on the long-term and seasonal courses of siltation in selected reservoirs in the Vistula drainage basin, Poland. The rate of sedimentation is analysed for both phases of siltation, and the useful lifetime of a reservoir, which corresponds to the first phase of siltation, has been computed according to a methodology proposed.

KEY WORDS dam; reservoir; silting; suspended load; trap efficiency; useful life of a reservoir; Vistula River

INTRODUCTION AND AIMS

Dams built across river valleys cause dramatic changes in the river transport of suspended material and bedload. Deposition of the material in a reservoir reduces its volume and drastically changes flooded valley morphology of the dam. The morphology of every reservoir, not subjected to flushing, is developed by two types of permanent sedimentation which comprise deltaic sedimentation (including accumulation of coarse material) and true bottom sedimentation (the siltation process) (Zhang and Long, 1980; Visher, 1981; Rust, 1982; Teisseyre, 1983; Cogollo and Villela, 1988). The development of morphology can be precisely quantified using data from repeated cross-section levelling, and can also be predicted by using different mathematical models of reservoir sedimentation which have recently been developed.

One of the basic problems of applied fluvial morphology is how to predict the time taken for the different stages of sedimentation in a non-flushed reservoir to be accomplished. Up until the present, Hartung's (1959) methodology for estimating *the useful life* of a reservoir, and also Pitt and Thompson's (1984) and Kabell's (1984) methodologies for calculating *the half-life* of a reservoir have been developed to predict this time. The useful life of a reservoir, when its operational functions are fulfilled, is the most important value and should be estimated in an economic analysis of planned investments based on reservoir use. Methodologies for computing the trap efficiency of a reservoir have been presented by numerous authors, and a criticism of them is presented by Heineman (1984).

Data relating to the time taken for different stages of reservoir siltation are rather scarce in the existing literature. Computation of these times using different methods gives diverging results (Bolton, 1984; Axelsson, 1992). Detailed data (geodetic, morphological, hydrological) relating to selected reservoirs in the Vistula drainage basin, Poland, as well as to many other reservoirs located in different morpho-climatic zones,

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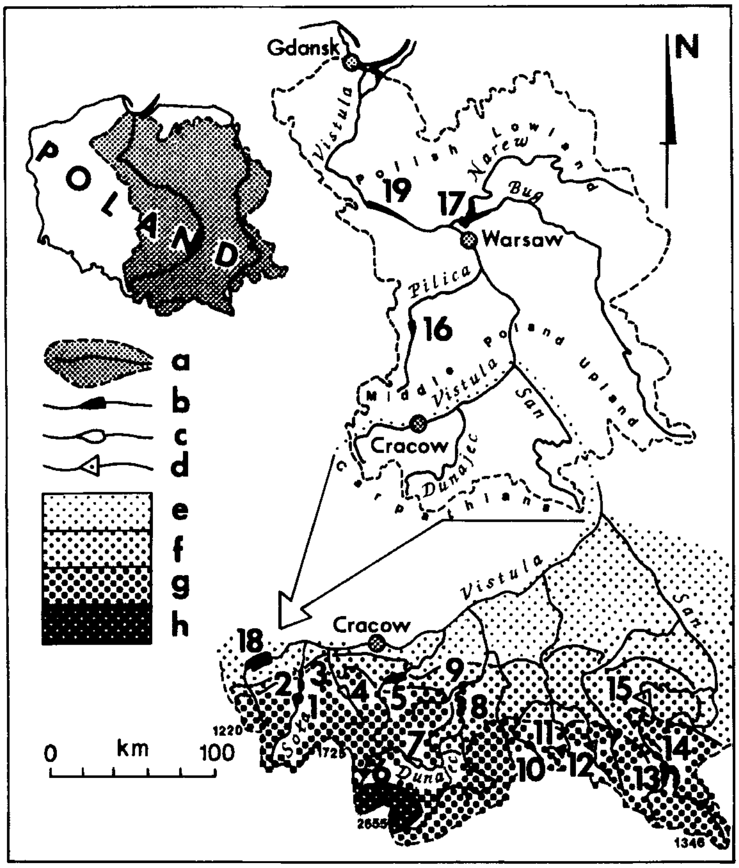

Figure 1. Location map. a, limit of the Vistula drainage basin. Dam reservoirs: b, existing; c, under construction; d, planned for the future. Morphological units in the Carpathians and their foreland: e, lowlandic foreland; f, Carpathian Foothill zone; g, medium and low mountains (the Beskidy Mts); h, high mountains (the Tatra Mts). Numbering of chosen reservoirs used: 1, Tresna; 2, Porabka; 3, Czaniec; 4, Swinna-Poreba; 5, Dobczyce; 6, Kojsowka; 7, Czorsztyn; 8, Roznow; 9, Czchow; 10, Klimkowka; 11, Krempna; 12, Dukla; 13, Solina; 14, Myczkowce; 15, Niewistka; 16, Sulejow; 17, Debe; 18, Goczalkowice; 19, Wloclawek

have been used to develop a model of the course of sedimentation in a reservoir not subjected to flushing, and to estimate the time taken for different phases of the sedimentation. The magnitude and time trend of suspended matter transport in a river downstream of a dam is affected by the course of reservoir siltation (Gong, 1987; Lajczak, 1989).

The specific aims of this study are:

1. to construct a general model of the course of the reservoir sedimentation;
2. to compare the presented model of the reservoir sedimentation with reconstructed long-term and seasonal courses of siltation of reservoirs in the Vistula drainage basin in the period from the start of operation until 1990, and selected to represent different hydrological types;
3. to propose methodology to estimate the useful life of a reservoir.

BRIEF DESCRIPTION OF THE VISTULA DRAINAGE BASIN AND RESERVOIR CHARACTERISTICS

Most of reservoirs in Poland lie within the Vistula drainage basin (Figure 1). The multipurpose reservoirs are situated on rivers with different mean discharges, hydrologic regimes, and rates of suspended load and bedload transport. Many reservoirs of widely various size are located on mountainous rivers in the Carpathians and their foreland.

Sedimentation of the study reservoirs is mainly due to material supplied by rivers, especially the suspended load which amounts to 90 per cent of the total solid transport in the Carpathian rivers, and to 50–90 per cent of the solid transport in lowland rivers. Bank erosion of reservoir supplies no more than 1 per cent of the total delivery to mountainous reservoirs, and more than 10 per cent to lowland ones. Silty-clay deposits are found in the reservoirs, and partially sandy deposits in the deltas. Small shallow reservoirs on mountainous streams may be filled up by gravel material.

Reservoirs on mountainous and upland rivers are either deep, with low water exchange, or shallow with quick water exchange. In the lowland part of the river basin both large and shallow, and also rather small and shallow reservoirs occur. Deep reservoirs in Poland are usually filled with water, and only some of the shallow reservoirs are occasionally flushed. Since the 1980s selected lowland reservoirs have been dredged.

DATA USED AND CALCULATION METHODS

The presented model of reservoir sedimentation is based on published data relating to reservoirs of various size and of different morphological and hydrologic types, which represent numerous morpho-climatic conditions. The discussed model is tested using detailed data relating to selected large or medium size reservoirs in Poland. The reservoirs are located on lowland or piedmont rivers of various size, and on a large Carpathian river, the Dunajec (Figure 1). The study reservoirs represent different morphological and hydrological types in Poland, and provide a sufficient base for testing the constructed reservoir sedimentation model (Lajczak, 1994, 1995). Long-term measurements of the suspended load in Polish rivers, which were initiated in the 1930s–1950s, are adequate to calculate the siltation rate of the study reservoirs, based on a balance of transport. Repeated measurements of reservoir capacity (every 5 years, on average) using acoustic instruments have allowed analysis of the progressive silting of the reservoirs and the development of their morphology. The methodology used in this part of the study is divided into two parts.

(A) First, the long-term and seasonal courses of siltation in the reservoirs supplied mainly by the suspended load, have been studied using the following data:

(a) daily measurements of suspended load in the period 1946–1990 for all gauging stations on rivers;
(b) daily water discharges for the same period;
(c) geometric parameters of the reservoirs.

Using the above data, the following equation was examined for each study reservoir:

$$\sum I_{\mathrm{mm(sl,bl,be)}} + \sum I_{\mathrm{om}} = O_{\mathrm{mm+om}} + \Delta S \tag{1}$$

where $\sum I_{\mathrm{mm(sl,bl,be)}}$ = the total input of mineral material (mm) as suspended load (sl), bedload (bl), and material from bank erosion (be); $\sum I_{\mathrm{om}}$ = the total input of organic material; $O_{\mathrm{mm+om}}$ = the output of mineral and organic material; ΔS = the rate of reservoir sedimentation.

Input of the suspended load to each study reservoir in every balance period (successive months and years) has been computed using the values recorded in the gauging stations located on rivers upstream. Average annual rates of the bedload delivery to the reservoirs, which is not regularly measured in the study rivers, have been evaluated on the basis of published ratios of the bedload rate and the suspended load rate in the rivers. The bedload is totally accumulated in the study reservoirs, except selected shallow ones which are occasionally flushed. Estimated rates of delivery of material which originates from reservoir bank erosion, are based on repeated levelling of the bank zone in numerous profiles. The results are published and discussed in the Polish literature. The total input of organic matter to the study reservoirs is based on published data relating to the content of this material in the total suspended load in the study rivers. The values correlate well with the mean content of organic material in accumulated sediments in the reservoirs (Lajczak, 1995).

The siltation rate of a reservoir can be expressed as an absolute ΔS value (tonnes/year, tonnes/month), and as a relative β value–trap efficiency, per cent. The β value allows easier comparison between reservoirs and is favoured in the study. The β parameter was calculated for the study reservoirs using Brune's (β_1),

Drozd's (β_2) and Hartung's (β_3) formulae, and by means of an equation describing the balance of transport:

$$\beta_4 = \frac{100(\sum I_{sl} - O_{sl})}{\sum I_{sl}} (\%) \tag{2}$$

The real trap efficiency β_5 of the reservoirs was calculated using the following formula:

$$\beta_5 = \frac{100 \left[\sum I_{mm(sl,bl,be)} + \sum I_{om} - O_{mm(sl)} - O_{om} \right]}{\sum I_{mm(sl,bl,be)} + \sum I_{om}} (\%) \tag{3}$$

(B) Secondly, the temporal course of siltation in the reservoirs was verified on the basis of the data obtained from repeated cross-section levelling, made every 5 years, on average. The mass of deposited sediment in the reservoirs in every balance period, obtained from Equation 1, was recalculated into volume using the following formula:

$$\Delta S = \frac{\beta_5 (\sum I_{mm} + \sum I_{om})}{\gamma_o} \tag{4}$$

where γ_o = a mean measured density (compactness) of deposited sediments ($1400\,\mathrm{kg\,m^{-3}}$).

The rate of reservoir siltation based on the balance of transport was calculated for different periods in the life of a reservoir as follows:

$$-\Delta S = \frac{100 \sum I \, n \, \beta_5}{V_i} (\%) \tag{5}$$

where $\sum I$ ($\mathrm{m^3\,a^{-1}}$) = the average annual total matter supply to reservoir; n = the number of years to exploitation; $V_i(\mathrm{m^3})$ = the initial capacity of the reservoir.

Later, the time taken for sedimentation in different stages of siltation in the study reservoirs is estimated. *The half-life* of each reservoir has been calculated according to the methodology of Pitt and Thompson (1984). *The useful life* can be estimated using Orth's (1934), Samov's (1959), and Goncarov's (1962) formulae, which describe a parabolic course for the silting process. The results presented in this study are based on the formula:

$$V_{st} = V_i \left[1 - \left(1 - \frac{v}{V_i} \right)^t \right] \tag{6}$$

where V_{st} = the silted volume of the reservoir after t years of its exploitation; v = the average annual volume of sediments deposited in the reservoir, calculated from a long period of measurement (equal to hitherto existing time of reservoir).

RESERVOIR SEDIMENTATION MODEL

Material input and shallowing process of the reservoir

Shallowing of reservoirs is caused by continuous retention of material supplied by the rivers, from bank erosion occurring round the reservoir, and occasionally from landslides which occur on slopes above the shoreline. Only the first source of material is present throughout the complete lifetime of a reservoir. Building of new dams upstream reduces the amounts of incoming material, and the transport of the bedload in the river downstream of a dam may be completely stopped.

The river load supply to reservoirs is controlled by numerous geographical factors of upstream catchment area, and especially by the impoundments on tributaries, and reaches variable rates in successive years. Average annual rates of matter supply are rather quasi-stable in long time periods and may be drastically reduced (especially the bedload) if new deep dams are built upstream. Reservoirs located in areas of high denudation are quickly silted up, and the rate of this process is controlled by the initial volume of the reservoir, the size of the river, and its hydrologic regime (Ward, 1980; Gong, 1987; Abdelhadi Lahlou, 1988; Zeng, 1989; Jehanno *et al.*, 1990; Tamburino, 1990). Removing material from the eroded banks of a reservoir to deeper areas is effective in mountainous reservoirs only during the first years of their exploitation and decreases rapidly in

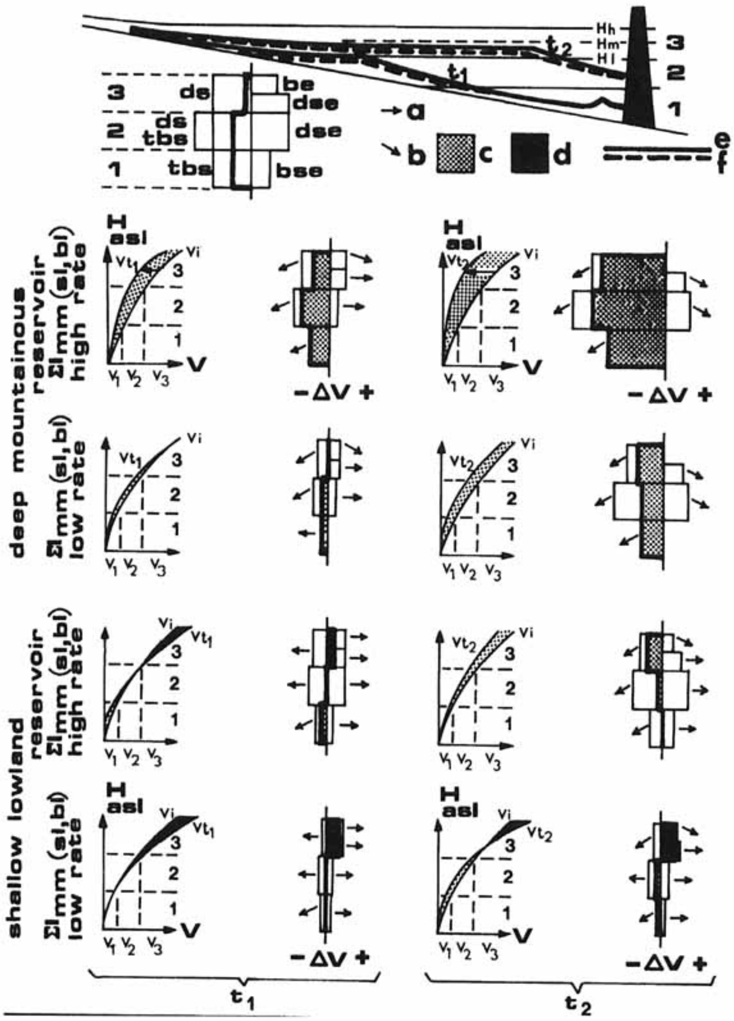

Figure 2. Sketch illustrating typical changes of volume, ΔV (positive values – increasing volume; negative values – decreasing volume), of three reservoir storages during the exploitation time, as represented by the initial stage, t_1, and the advanced stage, t_2, of the silting process. The storages are: 1, dead storage; 2, useful storage; 3, flood-protecting storage. This sketch is based on data resulting from repeated surveying of reservoirs in Poland. It shows typical changes of the ΔV values for deep mountainous reservoirs and shallow lowland ones, which are supplied by mineral material $\sum I_{\mathrm{mm(sl,bl)}}$ of high or low rate. Increasing reservoir storage is caused by the following processes: be, bank erosion; dse, deltaic sediments erosion; bse, bottom sediments erosion. Decreasing rates of reservoir storage are due to the following processes: ds, deltaic sedimentation; tbs, true bottom sedimentation. Intensity of the processes mentioned: a, stable; b, decreasing. Changes of reservoir volume: c, silted volume; d, increased volume of the flood-protecting storage. Surface of deltaic sediments in mountainous reservoirs: e, before large floods; f, after large floods. Water level in reservoir: H_l, low; H_m, mean; H_h, high. Relations between water level and reservoir volume, H–V, are also presented for separate storages. Reservoir total volume: V_i, during the first year of its operation; V_{t_1}, after t_1 years; V_{t_2}, after t_2 years

the case of resistant bedrock. Exposure of the harder rocks along the reservoir banks stops an effective waste supply to those reservoirs, in the flysch Carpathians for example (Cyberski, 1969). On the contrary, lowland reservoirs located in areas built by easily erodible deposits (e.g. loess, till, fine alluvia), and subjected to intensive waving, are characterized by much larger amounts of material originating from continuously eroded banks, which finally plays an important role in the reservoir shallowing during its whole lifetime (e.g. Butorin, 1969; Shirokov, 1974).

The three volumes of the reservoir are reduced: the dead storage, the useful storage, and the flood-protecting storage (Figure 2). The intensity of shallowing of the three sections of reservoir bottom, which are connected with the separated reservoir layers, depends on the rates of incoming material and the trap efficiency of

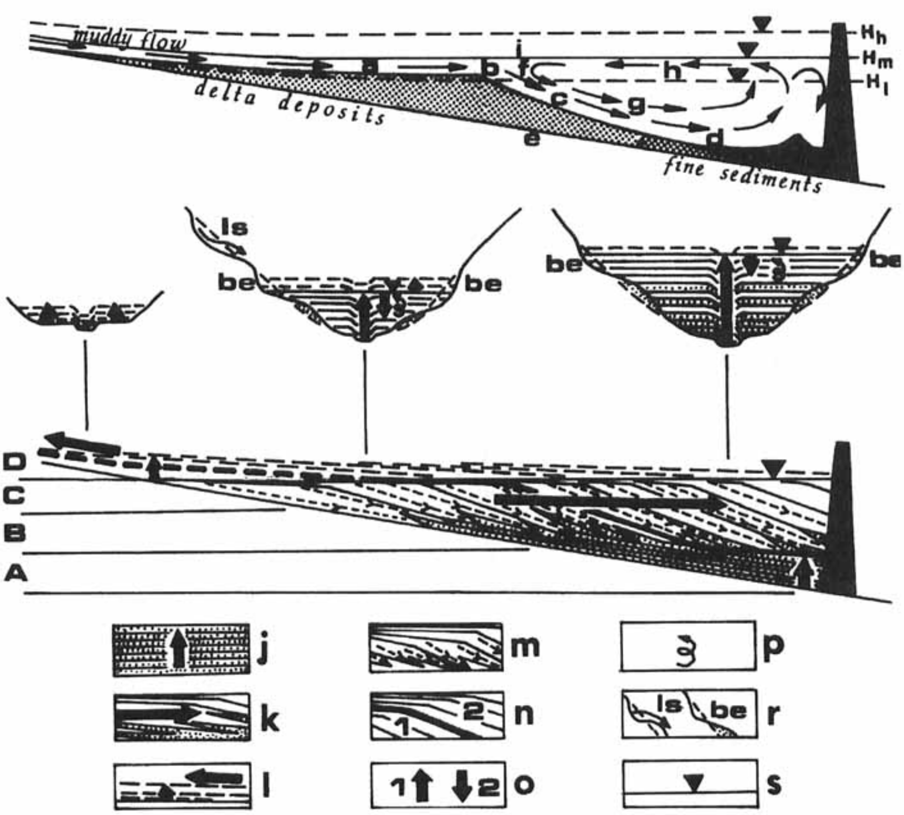

Figure 3. Water circulation in dam reservoir and morphological development of its basin (in longitudinal and transverse profiles): a, topset slope of the delta; b, Pivot point; c, foreset slope of the delta; d, bottomset slope; e, original thalweg slope; f, plunge point; g, density current; h, clear water; i, floating debris; j, increasing thickness of bottom sediments; k, direction of delta development; l, development of new channel level over filled-up reservoir basin; m, erosional and accumulation effects of density currents; n, sediments accumulated during the first (1) and the second (2) phases of reservoir silting; o, depth zones with dominant vertical directions of silting process (1, positive silting; 2, negative silting); p, depth zone with wave-induced sediment resuspension; r, reservoir bank remodelling (be, bank erosion; ls, landslides); s, water level (H_l-low, H_m-mean, H_h-high). Types of sedimentation: A, true bottom sedimentation (the siltation); B, both true bottom sedimentation and deltaic sedimentation; C, deltaic sedimentation; D, channel aggradation

the reservoir for the suspended load and the total load. Flushing operations and dredging practices introduce significant complications in the reservoir siltation process and prolong the reservoir life.

Permanent overbuilding of the bottom of a non-flushed reservoir results from delta development and true bottom sedimentation. The second type of sedimentation reduces mainly the dead storage of the reservoir and this process can be accelerated in shallow reservoirs, especially the lowland ones subjected to intensive waving, due to removal of material from eroded reservoir banks to deeper areas. The useful and flood-protecting storages of the reservoir are reduced by delta development, and this process plays the most dominant role in shallowing the deep valley reservoirs located on rivers, which transport the bedload at high rates (Figure 3).

Phases in the course of reservoir sedimentation

Continuous shallowing of a reservoir causes diminution in the area of active flow in the reservoir cross-section and this process is followed by an increase in flow velocity through the length of the reservoir, which leads to a decrease in the likelihood of sedimentation of particles, firstly transported as the bedload, and secondly as the suspended load (Sundborg, 1992a, b). The result of advanced shallowing of the reservoir is to quickly decrease to zero the trap efficiency, firstly for the river bedload, and later for the total river load. Rapid shallowing of lowland reservoirs, due mainly to remodelling of their banks, accelerates the decreasing trend in the trap efficiency for the total load and also the suspended load, e.g. in some lowland reservoirs in Poland (Lajczak, 1995).

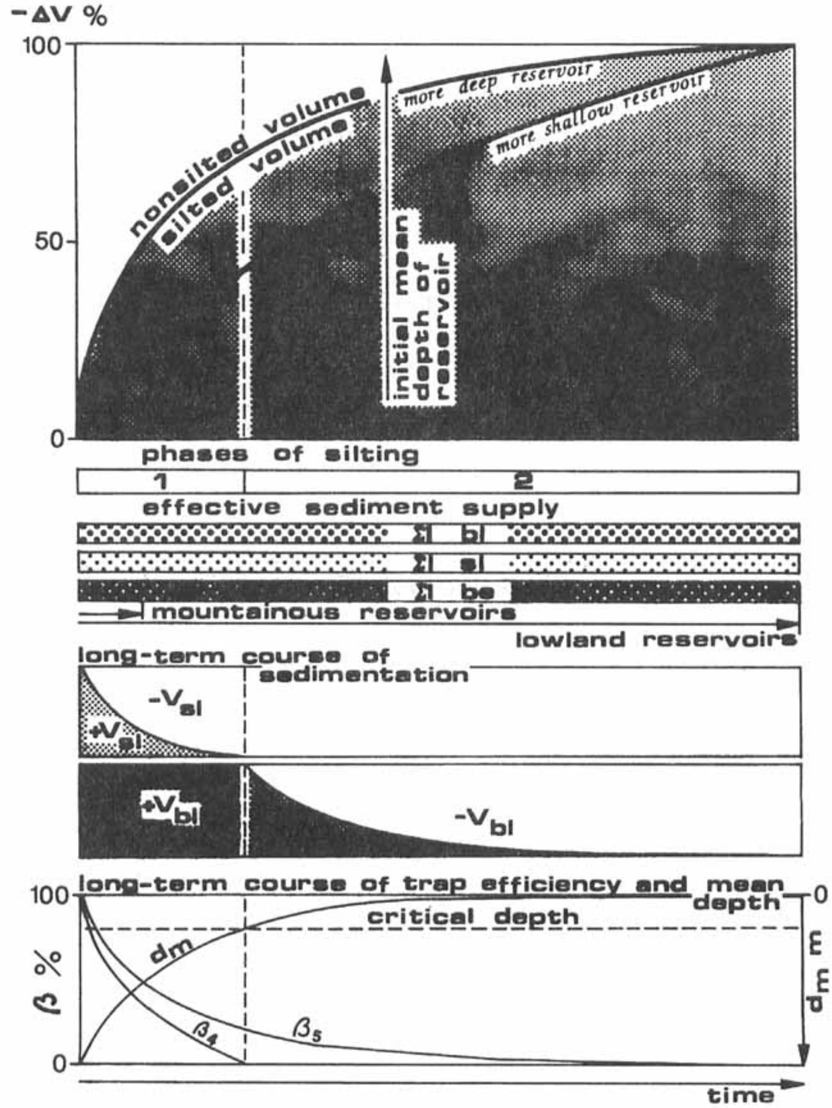

Figure 4. Model illustrating the long-term course of reservoir silting. For explanation of the symbols see text

The date presented in numerous publications (e.g. Zeng, 1989; Cheng, 1992; Lajczak, 1994, 1995) show that the time taken for sedimentation of reservoirs can be divided into two phases, characterized by different intensities in the shallowing process. These are (Figure 4):

(a) silting of a relatively deep reservoir;
(b) silting of an initially shallow reservoir or further silting of an initially deep reservoir which has experienced much shallowing.

This division is well confirmed by the data obtained from rapidly silted reservoirs, for example in loess and flysch areas located in semi-arid zones. Each phase of sedimentation differs in the absolute and relative sedimentation rates, the sediment outflow rates from the reservoir, and the rates of sedimentation due to different types of incoming material.

During the first phase of sedimentation each type of incoming material contributes to the accumulation of sediment in the reservoir. Rapid shallowing takes place during this phase of sedimentation involving each

source of material, and particularly the suspended load. The fine material is partially stopped in the non-flushed deep reservoir ($+V_{sl}$), and all of the incoming coarser material can contribute to the shallowing ($+V_{bl}$). The very clear decreasing trend in rate of siltation, which is specific for each reservoir, is due to the increasing amounts of the suspended load flowing out through the dams ($-V_{sl}$). The trap efficiency for the suspended load (β_4) consequently decreases, and only particles of bigger size transported as the bed-load can be deposited in the reservoir. Reservoirs of small size are usually quickly silted. The time taken to fill large reservoirs is much longer, in spite of their higher trap efficiency. The first phase of silting ends when the mean depth of a much shallowed reservoir reaches a critical value, which depends on hydrological conditions as the capacity of the reservoir is reduced (Figure 3). Then the trap efficiency for the suspended load (β_4) reaches zero. For example, in Poland the critical depth of studied reservoirs is about 5 m in mountainous reservoirs of large and medium size, and 3–4 m in lowland reservoirs of large and medium size, and about 2 m in the case of small and shallow reservoirs located on streams (Teisseyre, 1983; Lajczak, 1994, 1995).

During the second phase of sedimentation, reservoir shallowing takes place much more slowly, and is caused mainly by deposition of coarser particles of incoming material ($+V_{bl}$) (Figure 4). The effects of intensive wave-induced resuspension of bottom sediments, and of erosion by density currents in reservoirs on mountainous rivers, are approximately equal rates of the suspended matter inflow and outflow during a long period. In a short time period, the reservoirs play a role as net exporters of sediment; for example during periods of high flow, coarser material can be moved throughout the dams (Chomiak, 1960; Summer, 1990). The continuing decrease in the rate of shallowing is caused by increasing amounts of bedload outflow ($-V_{bl}$) from reservoirs with much reduced depth. The reservoirs attain a new dynamic equilibrium along their length, and periods with positive and negative balance for sedimentation alternate in successive months or years (Bhowmik *et al.*, 1988; Zeng, 1989; Cheng, 1992; Lajczak, 1994, 1995). At the end of this phase of sedimentation, the reservoir's depth and the trap efficiency for the total load (β_5) reach zero values. This phase of silting ends when the new river channel is formed along the completely filled up reservoir basin.

Changes in reservoir morphology during the course of sedimentation

A general model of the long-term course of reservoir sedimentation is presented in Figure 4. The course of sedimentation depends on the amounts of incoming material, the reservoir trap efficiency for the suspended load (β_4) and the total load (β_5), and the factors influencing intensity of waving (e.g. area, shape and mean depth of reservoir, denivelations in surroundings). The initial mean depth of the reservoir determines the progress of parabolic curve of reservoir silting. The intensity of this process is larger in deeper reservoirs in both phases of silting.

Permanent overbuilding of the bottom of a non-flushed reservoir is the counteracting factor, which controls the equilibrium of the reservoir bottom (Visher, 1981; Sundborg, 1992a, b). Due to seasonal water table fluctuations in the reservoir, density currents and wave-induced resuspension, the periodically deposited sediments are removed from shallow areas, the delta especially, and they are permanently deposited in much deeper areas, i.e. below a critical depth under conditions of the lowest water level in the reservoir (Teisseyre, 1983; Klimek *et al.*, 1990; Lajczak, 1994, 1995). The mean thickness of sediments varies in longitudinal profile of the reservoir depending on the granulometric composition of the incoming river load; this differentiation is most evident in reservoirs located on mountainous rivers which transport a large bedload (e.g. Visher, 1981). Thus, non-stable deltaic sedimentation causes the highest reduction of reservoir flood-protecting storage, and especially the useful storage. The true bottom sedimentation of the finest particles reduces only the dead storage of deep reservoirs (Figure 3).

Remodelling the reservoir banks causes an increase in the flood-protecting storage of the reservoir only in the case of a low rate of river load supply (Lajczak, 1995). A more advanced stage of development of mountainous reservoirs characterizes itself by the bank quasi-stabilization. Material removed from the eroded bank zone participates in reducing the useful and dead storages of the reservoir. In the case of large and shallow lowland reservoirs, especially those located in areas with easily erodible deposits, the bank remodelling process is usually followed by a continuous increase in the reservoir flood-protecting storage (Butorin, 1969; Shirokov, 1974) (Figure 3).

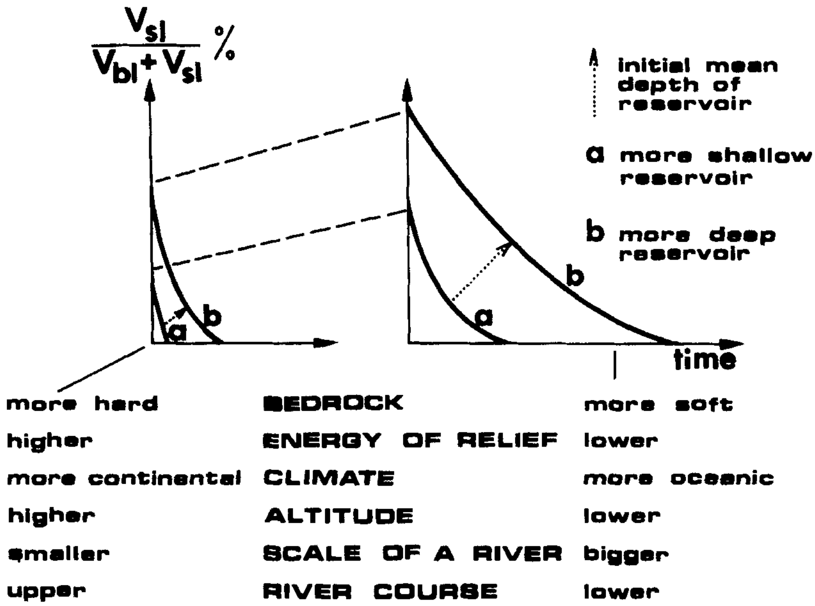

Figure 5. Sketch showing chosen environmental factors which impact the long-term course of the participation of the suspended load in the total mineral material accumulation in reservoirs of various size

The contribution of the suspended load to the total amount of mineral matter input to a reservoir is a very important factor influencing the rate and course of reservoir sedimentation. This factor depends on various environmental and anthropogenic conditions of the upstream catchment area. The contribution of suspended material to total mineral matter retention in a reservoir decreases during the lifetime of the impoundments (Figure 5). This figure, which is based on data from the study reservoirs in Poland and numerous others located in different morpho-climatic zones, shows that suspended sediment contributes to siltation for longer periods in deeper reservoirs.

The duration of the two phases of reservoir sedimentation depends on the geological, morphological and climatic conditions in the upstream catchment areas. In semi-arid areas, for example, reservoirs can become silted up even by fine material, which is not eroded during long dry periods. In high mountains consisting of resistant rocks, reservoirs quickly become silted, mainly by coarser material. Small reservoirs may become silted up even after a few years of operation (Orth, 1934; Bauer, 1968; Bauer and Burz, 1968; Cyberski, 1973; Gong, 1987; Abdelhadi Lalhlou, 1988; Zeng, 1989; Jehanno *et al.*, 1990; Tamburino, 1990). A similar situation has been recognized for very small mineral matter trap dams in the Polish flysch Carpathians, which are now completely silted up mainly by bedload (Froehlich, 1975; Lajczak, 1994, 1995). A rapidly decreasing trend in the sedimentation rates of reservoirs located on rivers of various sizes, which transport large loads, has been noted in numerous areas (e.g. Bauer, 1968; Bauer and Burz, 1968; Visher, 1981; Cheng, 1992; Lajczak, 1994, 1995).

Reservoir shallowing induces increased relative rates of bedload accumulation (Figures 4 and 5), and this trend has been investigated for selected reservoirs on mountainous rivers, which transport high bedloads (e.g. Bauer, 1968; Bauer and Burz, 1968; Cyberski, 1973; Lajczak, 1994, 1995). The advanced stage of development of small and shallow reservoirs on mountainous rivers in the flysch Carpathians characterizes itself by more intensive bedload accumulation during periods of high and very non-uniform discharges. Periods of low discharges are characterized by very slow siltation due to suspended load retention.

Most of the surveyed deep reservoirs in the world are at the beginning of the first phase of the silting process. Only in reservoirs of smaller size, which are located on rivers with a large load, is this process more advanced. Much shallowed reservoirs and new shallow reservoirs are at the beginning of the second phase of the silting process. Numerous reservoirs in highly denuded areas, e.g. the semi-arid zone, are at the end of the silting process and many of them have been completely silted up for several years.

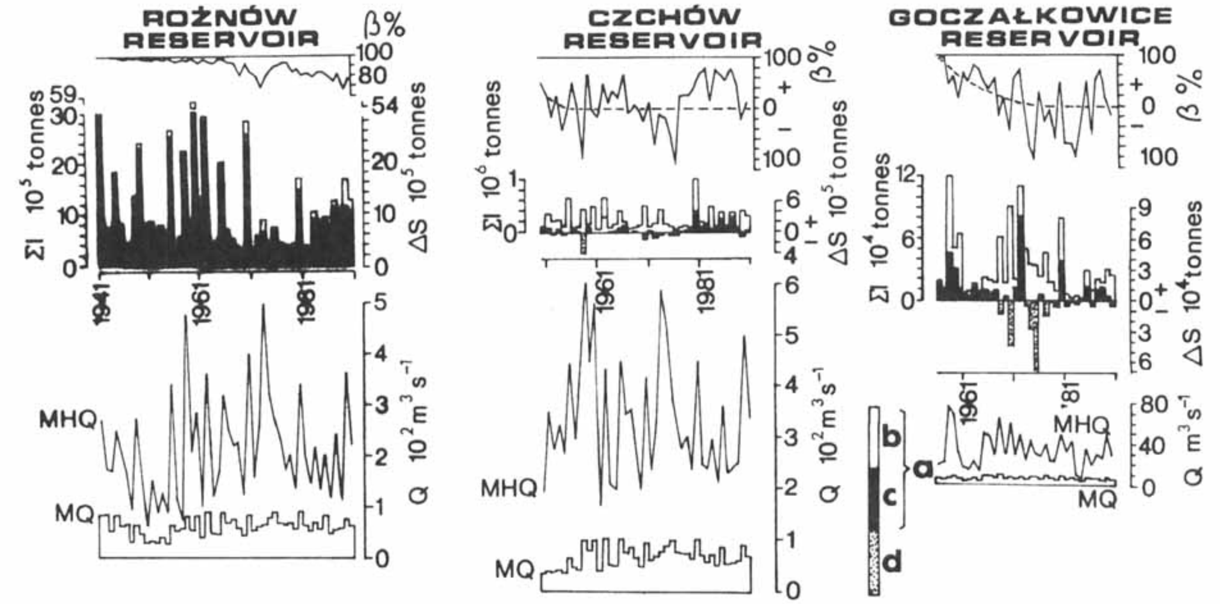

Figure 6. Long-term course of silting of chosen dam reservoirs. For location of the reservoirs see Figure 1. An annual values of: a, suspended load inflow $\sum I$; b, suspended load outflow; c, positive silting $+\Delta S$; d, negative silting $-\Delta S$; β, trap efficiency for suspended load; MQ, mean discharge; MHQ, mean high discharge of the main river upstream of the reservoir

COMPARISON OF THE RESERVOIR SEDIMENTATION MODEL WITH RECONSTRUCTED COURSES OF SILTATION OF SELECTED RESERVOIRS IN THE VISTULA CATCHMENT BASIN

Long-term course of siltation based on the balance of transportation

Figure 6 presents changes in absolute, ΔS, and relative, β, values for three selected reservoirs representing deep mountain reservoirs (Roznow), shallow mountain reservoirs downstream associated with a deep reservoir (Czchow), and large shallow lowland reservoirs (Goczalkowice), together with variations in water supply and material input ($\sum I$) to and output (O) from the reservoir during their existence (until 1990). In addition, 5 year mean values of the β parameter are presented in Table I for 11 reservoirs representing the groups of reservoirs studied.

In the case of reservoirs which do not receive large amounts of suspended load, the β parameter, which is represented by the β_1, β_2 and β_3 values, is relatively stable during the first few decades of operation, when reservoir volume is not reduced too much. Only the rapidly silted Roznow Reservoir shows a clear decreasing trend in the β parameter. In contrast, intensive dredging practices in the large lowland reservoirs have caused increasing values of the β parameter for the last 10 years studied (Lajczak, 1995). The β_4 values show much more precisely the changes in the trap efficiency for the suspended load of each studied reservoir.

In rapidly silted deep reservoirs located on large Carpathian rivers with high suspended load, such as the Roznow Reservoir, the ΔS and β values continuously decrease. This trend is independent of large variations in material supply in successive years. A considerable decrease in trap efficiency was clearly noted for years with catastrophic floods, but only after a certain critical magnitude of sedimentation had been reached. In years following large floods, the deltaic deposition is temporarily subjected to strong erosion. For the last 15 years a rapid decrease in trap efficiency has occurred during a period of relatively small floods. In 1990, the β parameter reached 76 per cent. In future years, catastrophic floods will markedly decrease the trap efficiency and the process described above will intensify. Rates of suspended material outflow have clearly increased during the life of the reservoir.

In Czchow Reservoir, which is a shallow valley reservoir located downstream of a deep impoundment on a large Carpathian river with high suspended load, sediments are deposited only during smaller floods. The sediments are eroded during high discharges, as a result of operations in the deep reservoir upstream,

Table I. Five-year mean values of the trap efficiency β of chosen function reservoirs in the Vistula drainage basin during their time of existence. A = average β values for the whole period of the reservoirs' exploitation. For explanation of the symbols β (β_1, β_2, β_3, β_4) see text

		Years											
Dam reservoir	β	1938 1940	1941 1945	1946 1950	1951 1955	1956 1960	1961 1965	1966 1970	1971 1975	1976 1980	1981 1985	1986 1990	A
Tresna	1							90	90	90	90	90	90
	2							91	91	91	91	91	91
	3							93	93	93	93	93	93
Porabka	1	77	77	77	77	77	77	77	77	77	77	77	77
	2	82	82	82	82	82	82	82	82	82	82	82	82
	3	80	80	80	80	80	80	80	80	80	80	80	80
Solina	1							97	97	97	97	97	97
	2							98	98	98	98	98	98
	3							100	100	100	100	100	100
Roznow	1		86	86	85	84	84	84	83	83	82	82	84
	2		91	91	91	90	90	90	89	89	88	88	90
	3		88	87	87	86	86	86	85	85	84	84	86
	4		99·5	98·6	97·2	96·3	95·6	90·6	80·1	89·2	81·5	78·7	93·3
Czchow	1				25	25	25	25	25	25	25	25	25
	2				30	30	30	30	30	30	30	30	30
	3				0	0	0	0	0	0	0	0	0
	4				5·9	0·0	51·5	33·3	0·0	21·2	50·4	14·6	21·8
Myczkowce	1						60	44	44	44	44	44	47
	2						68	50	50	50	50	50	53
	3						65	45	45	45	45	45	48
Czaniec	1							0	0	0	0	0	0
	2							0	0	0	0	0	0
	3							0	0	0	0	0	0
Goczalkowice	1					96	96	96	96	96	96	96	96
	2					97	97	97	97	97	97	97	97
	3					100	99	99	99	99	99	99	99
	4					79·1	72·0	60·7	28·8	46·0	0·0	0·0	44·6
Wloclawek	1							54	52	52	54	55	53
	2							56	54	54	56	57	55
	3							56	54	54	56	56	55
	4							48·2	36·0	23·7	29·5	67·8	42·7
Debe	1						53	45	43	42	44	45	45
	2						53	45	43	42	44	45	45
	3						56	50	45	42	47	50	48
	4						67·8	46·8	26·8	12·5	32·3	22·7	34·8
Sulejow	1								84	84	87	90	86
	2								86	86	89	92	88
	3								86	88	90	91	89
									56·7	40·4	0·0	0·0	13·4

and also during the course of flushing operations in the Czchow impoundment (Lajczak, 1995). Periods of considerable sedimentation and strong erosion alternate in successive years in this reservoir, and the trap efficiency for the suspended load (β_4) dropped to 0 per cent in 5 years, and later fluctuated around a value of zero. In long periods without catastrophic floods, sedimentation occurred and annual β_4 values reached high rates. In the event of future catastrophic floods, the critical rates of reservoir siltation will decrease and the trap efficiency β_4 will become negative again. In the long term, rates of the suspended material outflow will approximately balance the rates of sediment inflow for this reservoir.

Another very shallow valley reservoir located on a Carpathian river downstream of two deep reservoirs, Czaniec Reservoir (see Figure 1), which has suffered practically no siltation, exhibits a value of zero for its

trap efficiency during its lifetime (Table I). In contrast, the trap efficiency of the Myczkowce Reservoir (see Figure 1), which is a shallow impoundment located on the upper stretch of a large Carpathian river, was drastically reduced after a large and deep upstream reservoir had been completed. Rapid silting of the reservoir occurred until 1967 but was stopped by intensive current erosion of bottom deposits, which resulted from the operation of the deep reservoir upstream.

In large lowland reservoirs, which are usually shallow, in spite of very varied hydrological regimes of rivers and suspended loads a rapid decrease of the ΔS and β parameters is also observed (Lajczak, 1994, 1995). In the Sulejow Reservoir (see Figure 1), which is located on a river with low and rather uniform discharges and with low suspended load, the ΔS and β parameters dropped to zero values in 12 years. This reservoir is subjected to intensive wave action and the rapid decrease of the ΔS and β parameters can be explained as a result of considerable reservoir shallowing due mainly to wave-induced remodelling of the bottom morphology. The situation presented is confirmed by the course of siltation in two other shallow reservoirs, which have quite different hydrological properties. In the Debe Reservoir (for location of the reservoir see Figure 1), which is located on a much bigger river characterized by uniform discharges and high suspended load, the ΔS and β parameters reached zero values in 20 years. The same time was taken for the trap efficiency to reach zero in the Goczalkowice Reservoir (Figure 6), located on the upper stretch of the Vistula River in the lowland foreland of the Western Carpathians. In the latter case, the river has a typical mountainous regime and sediment input is relatively low. In this reservoir an increasing trend in rates of suspended material outflow has been observed. The Wloclawek Reservoir, which is located on the lower stretch of the Vistula River (Figure 1) and is characterized by relatively uniform discharges and a large suspended load, has undergone rapid sedimentation and shown a rapid decrease in the ΔS and β parameters. During the first 13 years of its life the trap efficiency decreased from 80 to 35 per cent. This trend was stopped by the very intensive dredging practices started after 1982. Now, the β parameter is 80 per cent again, but if the dredging practices in the reservoir are stopped, its trap efficiency will reach 0 per cent in about 150 years (Lajczak, 1995).

An analysis of the high discharges in the rivers upstream of the reservoirs shows that it was only after a period of critical shallowing—partially due to accumulation of suspended material, that flood currents started to cause erosion to such an extent that the yearly balance of the reservoir silting became negative (Figure 6). In later years, this effect of erosion was observed even for lower peak discharges, and there is an alternation of the years with negative and positive balance of siltation. This means that, with maximum accumulation of sediments in shallow lowland reservoirs, a high rate of erosion of these sediments can easily be caused by flood currents. During the first years of a reservoirs' life the action of the currents was less efficient. Erosion of bottom sediments in the shallow lowland reservoirs is periodically due to intensive wave-induced resuspension. In the lowland reservoirs, in contrast to the shallow ones on mountainous rivers, the greatest sedimentation occurs in the years with the highest floods.

Seasonal variations in reservoir siltation derived from the balance of transportation

The decreasing trap efficiency values of the study reservoirs in Poland for suspended material are well illustrated by the seasonal variations in material retention, ΔS (Figure 7).

An analysis of the sedimentation during individual 5 year periods for the deep valley reservoir (Roznow) reveals a clear growth in the seasonal fluctuations of the trap efficiency. An increasing number of months per year during which there is a smaller trap efficiency, is observed. The trap efficiency is still positive ($\beta > 0$ per cent) in every month in the studied 5 year periods, and the lowest values are reached in the winter months owing to higher water viscosity.

A shallow valley reservoir located on a mountainous river (Czchow) shows an irregular pattern of seasonal fluctuations in the trap efficiency during individual 5 year periods. Except during the last 10 years (a period without a catastrophic flood), the number of months per year for which there is a negative silting balance ($\beta < 0$ per cent) is rather stable. On average for the lifetime of this reservoir, a negative balance was found only in July, which confirms that in a large Carpathian river with very reduced load from a deep upstream reservoir, currents play the dominant role in the erosion of sediments for shallow reservoirs of the cascade system.

In contrast to the Czchow Reservoir, the large and shallow reservoirs on the lowland rivers exhibit a clear growth in the number of months per year during which there is a negative balance for sedimentation.

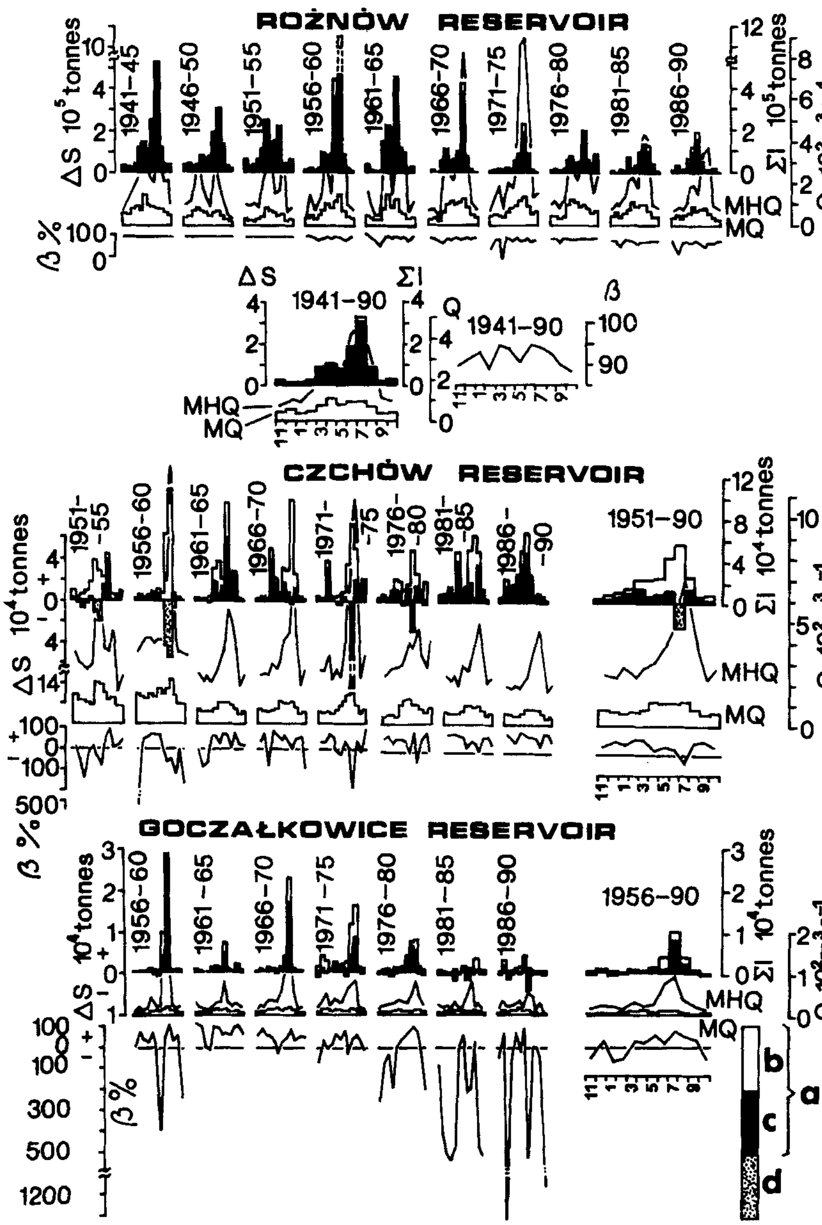

Figure 7. Seasonal variations in the silting rates of chosen dam reservoirs, expressed as mean monthly values in successive 5-year periods of their existence, and mean monthly values during the existing time of the reservoir. For location of the reservoirs see Figure 1, and for explanation of the symbols (a, b, c, d, β, MQ, MHQ) see Figure 6. Numbering of months: 1, January, ..., 12, December

Increasing rates of erosion have been found for these reservoirs in successive 5 year periods, but on average for the lifetime of these impoundments a negative balance was found only for the winter months, and additionally for the autumn months in the case of the Goczalkowice Reservoir. With progressive silting of these reservoirs the siltation balance became negative at first for the winter months, and later for other seasons (Lajczak, 1995). In winter and also in autumn, when the suspended material input is very low, the output of suspended material is greater than the input. This fact is further proof of a high contribution of wave-induced bottom sediment resuspension to the erosion of the bottom of the reservoirs.

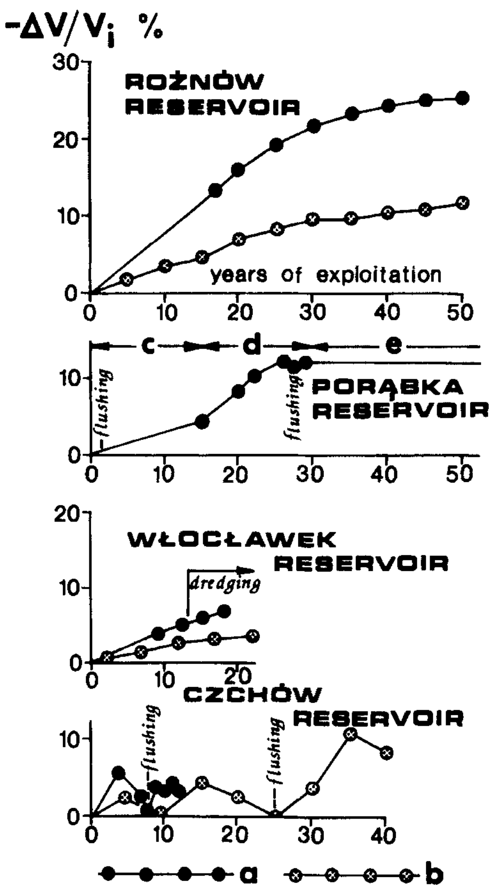

Figure 8. Long-term course of annual rates of chosen reservoirs' capacity losses, $-\Delta V/V_i$, based on repeated levelling (a) and the suspended load balance (b). Periods of the Porabka Reservoir exploitation time: c, partially filled reservoir; d, totally filled reservoir; e, totally filled reservoir associated with upstream of the Tresna deep reservoir

Long-term course of silting of the reservoirs, based on repeated levelling

Long-term changes in the trap efficiency of the different types of reservoirs investigated in the present study, are confirmed by a programme of repeated levelling in selected reservoirs (Figure 8). The repeated measurements of reservoir capacity reveal a parabolic decrease in the rates of reservoir siltation. This tendency is evident for the different types of reservoir, and especially for those experiencing rapid siltation.

The study reservoirs have been silted at different rates. The highest rates of sedimentation, expressed as the percentage of initial volume lost and calculated by Equation 5, are typical for the most headward reservoirs on a river. Reservoirs located downstream of deep one become silted up at a slower rate. The building of new dams upstream, and also dredging practices, make siltation much slower (Lajczak, 1995).

The volume of deposited material calculated using the data obtained from geodetic surveying is similar or larger than the volume obtained from data on river transport (Figure 8). Estimates based on levelling may be too large because the newest bottom deposits are formed as a gel, while estimates based on river loads may be too low because river sampling may fail to monitor all of the sediment transport. The real rate of reservoir siltation is likely to lie between the volumes obtained from these two sources of information.

TIME TAKEN FOR RESERVOIR SEDIMENTATION EXPRESSED BY THE STUDY RESERVOIRS IN THE VISTULA DRAINAGE BASIN

The time taken for reservoir sedimentation has been estimated for the two stages of filling. Good information

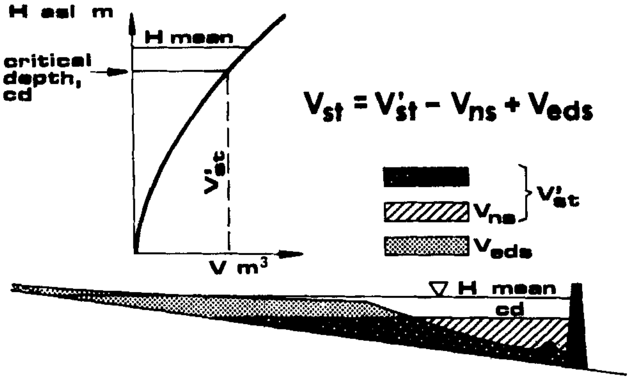

Figure 9. Sketch showing how to predict the limit of reservoir silting, V_{st}. For explanation of the symbols see text

on suspended load transport in the studied rivers allows the time taken for the first phase of sedimentation to be accurately estimated. In contrast, only imprecise information on average rates of bedload transport, which is low in the studied rivers compared with the suspended load, makes it impossible for a more detailed estimate of the time taken for sedimentation during the second phase.

The useful lifetime of the reservoirs

The useful lifetime (ULT) of initially deep reservoirs with seasonal water table fluctuations of more than 10 m, lasts until the useful storage capacity becomes completely silted. Later, the much shallowed reservoir no longer preserves its retentive role. Large lowland reservoirs may preserve the initial roles for much longer periods. In contrast to deep mountainous reservoirs, their useful lifetime can be identified not only with a first phase of sedimentation, but also with a long part of the second phase of sedimentation (Lajczak, 1994, 1995).

The useful lifetime of the deep reservoir has been predicted using Equation 6. A limit to sedimentation, V_{st}, which corresponds to 80 per cent loss of initial capacity (Hartung, 1959), is still accepted in numerous papers. In this study a real limiting value specific for each studied reservoir is used. The limit is reached when the reservoir's mean depth is reduced to the critical value, and this was estimated separately for individual reservoirs using their initial $H-V$ relationships (Figure 9). A preliminary V_{st}' value is derived from the $H-V$ relationship of an existing reservoir during the first year of its operation. In the reservoirs under construction and those planned for the future, the $H-V$ relationship has been calculated on the basis of the reservoir's bathymetric plan and its planned depth. The limit for sedimentation, V_{st}, is not defined by the horizontal surface corresponding to the critical depth, but by the surface of bottom sediments, which is more or less parallel to the original thalweg slope. Therefore, the estimated V_{st}' value must be reduced by the non-silted volume of the shallowed reservoir lying under the critical depth (V_{ns}), which is estimated from the probable bathymetric plan of the reservoir when the mean depth reaches the critical value. The V_{st}' value must also be increased by the volume of the periodically exposed deltaic sediments during low water tables in the reservoir, V_{eds}.

In the calculations, two initial parameters were taken into account. These were the long-term average annual sedimentation in each reservoir, based on the balance of transportation, ΔS, and the actual average loss of storage capacity of the reservoir, based on the repeated surveys. The results are presented in Table II; the ULT_1 values have been computed using the first data, and the ULT_2 values have been computed on the basis of the second data. The results show that useful lifetime is much longer for reservoirs located in the upper densely forested stretches of mountainous valleys, where suspended sediment yields are small.

The useful lifetime versus the half-life of the reservoirs

For the study deep reservoirs their half-life (HLT) is usually shorter than the useful lifetime (Table II). The data included in this table suggest that the difference between useful lifetime and half-life vary roughly

Table II. The useful lifetime, ULT, and the half lifetime, HLT, of chosen deep reservoirs in the Vistula drainage basin. Reservoirs: F, function; UC, under construction; P, planned for the future. For explanation of the symbols ULT_1 and ULT_2 see text

River	Dam reservoir	ULT (years)		HLT (years)
		ULT_1	ULT_2	
Wisloka	Krempna P	11 000	10 000	7000
Ropa	Klimkowka F	11 000	10 000	7000
Jasiolka	Dukla P	9600	9000	8000
Dunajec	Kojsowka P	9600	9000	8000
San	Solina F	8700	9000	8500
Skawa	Swinna-Poreba UC	2500	1300	1200
San	Niewistka P	900	800	520
Dunajec	Czorsztyn UC	810	710	700
Sola	Tresna F	680	620	520
Raba	Dobczyce F	680	620	650
Dunajec	Roznow F	320	260	230

in proportion to the initial mean depth of the reservoir. Thus, the half-life for deep reservoirs generally represents a younger stage in their siltation.

The useful lifetime versus the time taken for shallowed reservoirs to be completely filled

The time taken for complete reservoir filling has been predicted on the basis of the ratio of suspended load and bedload transport in the rivers upstream of the individual reservoirs. In the study area, this time is much longer than the useful lifetime of the reservoirs, although the difference between these values decreases in areas with relatively greater bedload transport. For example, in the western part of the Polish flysch Carpathians the second phase of non-flushed reservoir sedimentation will probably be a minimum of 10 times longer than the first (Lajczak, 1995).

CONCLUSIONS

The reservoirs studied in Poland are subjected to rather slow sedimentation if compared with the reservoirs located in highly denuded areas. The computed useful lifetime, even for reservoirs undergoing the most rapid sedimentation in the study area, is a sufficient basis for water management in Poland (Lajczak, 1995). The calculated lives of the reservoirs are valid only for present-day land-use and climatic conditions. The times are also valid only for reservoirs which are not affected by dredging practices and flushing operations, and until new dams are constructed upstream. Surveys of selected reservoirs in Poland demonstrate that a cascading system of reservoirs extends the lifetime of the reservoirs lying downstream.

The method used in this study for calculating the useful lifetime of a reservoir can be adopted in other cases. A fixed limit of 80 per cent filling (Hartung, 1959), which is still accepted, should be replaced by the real value which is specific for individual reservoirs.

The curvilinear nature of the sedimentation rate for every reservoir, not subjected to dredging practices and flushing operations, shows that the first 50 per cent of capacity is silted up much more quickly than the remainder. This means that the term '*half-life*' is not an adequate index of useful life for deep reservoirs, especially those studied in the present investigations.

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